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LIGHT MESON SPECTROSCOPY: RECENT DEVELOPMENTS and DAFNE

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ABSTRACT

In this contribution I discuss recent developments in light meson spectroscopy, and note specific areas in which DAFNE is an especially appropriate tool for future experiments. One topic of special relevance is the spectroscopy of excited vector mesons; quite narrow vector hybrids are predicted by the flux-tube model, which could be produced by DAFNE when operating in the $M_{e^+e^-} \approx 1.5 - 2$ GeV range. A second topic, which would be appropriate for a later date because it requires a rather higher beam energy, is the production of C=(+) mesons in $\gamma\gamma$ collisions.

1 Introduction

The last few years have seen rapid and exciting developments in light meson spectroscopy, largely as a result of the analysis of high-statistics experiments

using hadron beams. The most notable discoveries have come from studies of $P\bar{P}$ annihilation at LEAR and $\pi^- P$ at the AGS (BNL) and VES (Serpukhov). In both processes we have seen that detailed amplitude analyses of high-statistics events samples (ca.1M events) have made possible the identification of very interesting parent resonances in otherwise relatively mundane final states such as 3π. This has led for example to the discovery of a glueball candidate in $3\pi^o$ and an exotic hybrid candidate in $(3\pi)^-$. Concurrently we have seen impressive progress in the study of conventional $q\bar{q}$ mesons (which must be identified as a background to more unusual resonances), and at this meeting we have heard important new results from VEPP which appear to confirm the predictions of Close, Isgur and Kumano for a $K\bar{K}$-molecule assignment for the scalars $f_0(980)$ and $a_0(980)$. In this case at least, progress has come from an e^+e^- facility rather than a hadronic one. In this introduction I will give a brief summary of the status of the various sectors of meson spectroscopy, and then discuss two areas in which DAFNE can make very important contributions, excited vectors and C=(+) mesons.

2 Recent developments in light meson spectroscopy.

2.1 Glueballs

The gluonic degree of freedom in QCD leads to more physical resonances than are predicted by the naive $q\bar{q}$ quark model. Pure-glue "glueball" states have been studied using many theoretical approaches, the most recent and (presumably) the most accurate of which is lattice gauge theory (LGT). In recent years LGT has largely displaced other theoretical methods for treating these most unfamiliar of hadrons. A recent high-statistics LGT study of the glueball spectrum to ca.4 GeV has been reported by Morningstar and Peardon [1)](see Fig.1); for other recent discussions of glueballs and LGT see Teper [2)] and Michael. [3)] The lattice predicts that the lightest (assumed unmixed with $q\bar{q}$) glueball is a scalar, with a mass of about 1.7 GeV. Additional glueballs lie well above 2 GeV, with a 0^{-+} and a 2^{++} appearing at masses of $\approx 2.4 - 2.6$ GeV. Spin-parity exotic glueballs are expected at rather higher masses; in the Morningstar and Peardon study the lightest exotic glueball was found to be a 2^{+-} at just above 4 GeV. For experimental studies of meson spectroscopy below ca.2.2 GeV, the subject of glueballs thus reduces to the search for an extra scalar.

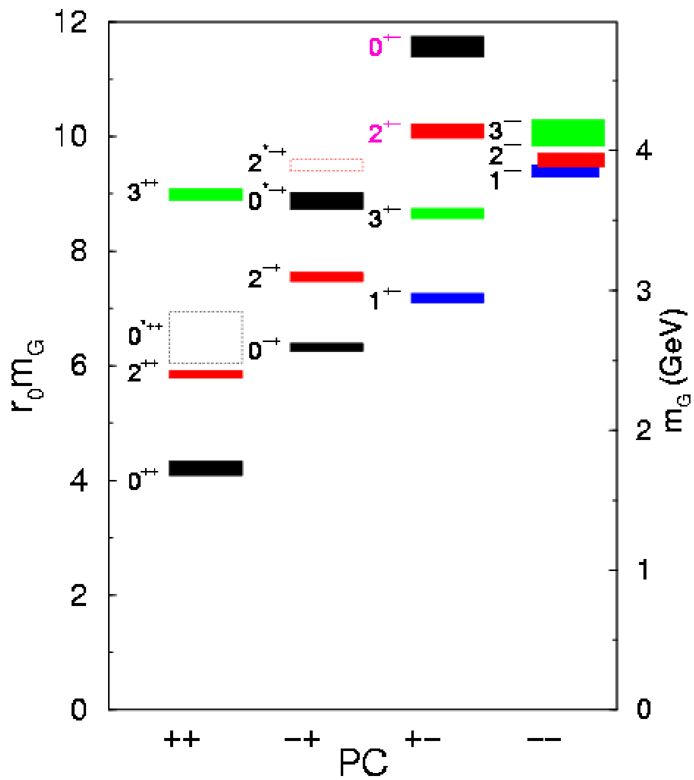

Figure 1: *The spectrum of glueballs found by Morningstar and Peardon in pure glue LGT.* [1] *The lowest scalar has a predicted mass of 1.73(5)(8)GeV.*

Scalars unfortunately comprise the most obscure part of the spectrum, and there are at least three states that might *a priori* be identified with a scalar glueball, the $f_0(1370)$, the LEAR state $f_0(1500)$ [5] and the ψ radiative candidate $f_0(1710)$. [6]

There are outstanding problems with each of these assignments. In view of LGT mass predictions the $f_0(1500)$ and $f_0(1710)$ appear most plausible, but neither of these states shows the flavor-blind pattern of decay couplings naively expected for a flavor-singlet glueball. The $f_0(1500)$ as seen by Crystal Barrel in $\pi^o\pi^o$ is shown in Fig.2. The results of some analyses, taken from the 1998 PDG, are shown in Table 1. Although essentially all these numbers are controversial, it is clear that the $\pi\pi/K\bar{K}$ branching ratios of the $f_0(1500)$ and $f_0(1710)$ are both far from the approximate equality expected for a flavor-singlet. We also note that the two lighter states have large 4π modes, which

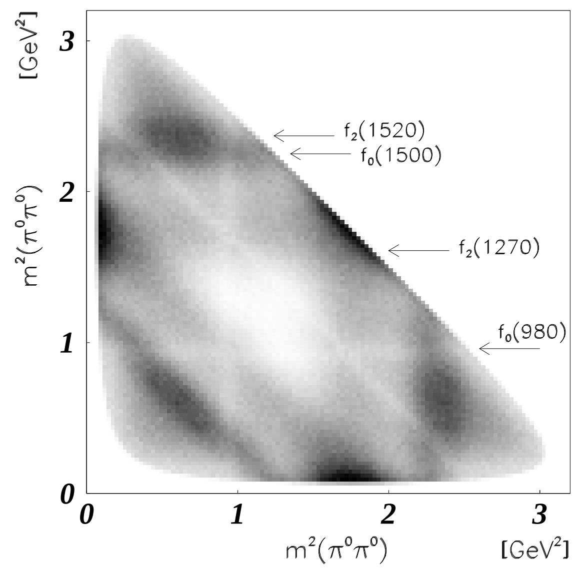

Figure 2: *The scalar glueball candidate* $f_0(1500)$ *observed by the Crystal Barrel Collaboration* [8] *in* $P\bar{P} \to \pi^o(2\pi^o)$.

have not been considered in glueball decay models.

The $K\bar{K}$ mode of the $f_0(1500)$ is difficult to isolate, but appears to be weaker than one would expect for flavor-singlet couplings to $\pi\pi$, $K\bar{K}$ and $\eta\eta$. Conversely, the $f_0(1710)$ has a strong $K\bar{K}$ mode but a weak $\pi\pi$ coupling. The determination of the $K\bar{K}$ branching fraction of the $f_0(1500)$ has recently been reanalysed by Ableev *et al,* [7] who find a much larger branching fraction than quoted in Table 1, but still rather smaller than expected for a flavor singlet. Several models, for example that of Amsler and Close, [5] invoke important $n\bar{n} \leftrightarrow G \leftrightarrow s\bar{s}$ mixing to explain the observed branching fractions these scalar states, so the scalar glueball basis state may actually be distributed over several physical resonances. In the final section we will discuss how this possibility could be tested at an e^+e^- facility.

For completeness we note that BES has reported evidence for a possible

Table 1: *Some two-pseudoscalar branching fractions of f_0 states quoted by the PDG.* [4]

Mode:	$\pi\pi$	$K\bar{K}$	$\eta\eta$	$\eta\eta'$	$\eta'\eta'$
singlet/k_f:	3	4	1	0	1
B_i (expt.):					
$f_0(1370)$	26% (9%)	35% (13%)	seen	-	-
$f_0(1500)$	45.4% (10.4%)	4.4% (2.4%)	seen	seen	-
$f_0(1710)$	$3.9\%^{+0.2\%}_{-2.4\%}$	$38\%^{+9\%}_{-19\%}$	$18\%^{+3\%}_{-13\%}$	-	-

narrow state in several channels, including $P\bar{P}$, $\pi\pi$, $K\bar{K}$ and $\eta\eta$, at about 2.2 GeV. [9] Although one does expect a tensor glueball not far above this mass, and the narrow glueball candidate $f_0(1500)$ suggests that the tensor glueball might have a narrow width, the statistical significance of the reported signals near 2.2 GeV is rather low. Another problem is that the Crystal Barrel has shown that the $P\bar{P}$ and $\eta\eta$ modes cannot both be as large as claimed by BES, since the state does not appear with the corresponding strength in $P\bar{P} \to \eta\eta$. This state clearly "needs confirmation".

2.2 Hybrid Mesons

In addition to glueballs, we also expect the glue degree of freedom to lead to "hybrid mesons" in which the $q\bar{q}$ pair is combined with glue in an excited state. Hybrids are especially attractive experimentally, because they span flavor nonets (so they can be searched for in many flavor channels), and have "exotic" J^{PC} combinations such as 1^{-+} that are forbidden to $q\bar{q}$ states. (Hybrids span *all* J^{PC} quantum numbers, both exotic and non-exotic.) The J^{PC} content of the lowest-lying hybrid multiplet is model dependent: The lowest-lying exotics in this first hybrid multiplet according to the flux-tube model are

$$J^{PC}(\mathrm{lightest\ flux-tube\ hybrid\ exotics}) = 0^{+-}, 1^{-+}, 2^{+-} \tag{1}$$

and are expected to be approximately degenerate. In contrast, in the bag model the lightest hybrid multiplet only has the single exotic

$$J^{PC}(\mathrm{lightest\ bag-model\ hybrid\ exotic}) = 1^{-+}\ . \tag{2}$$

The difference is due to assumptions about confinement; the bag model has a confining boundary condition that discriminates between color electric and

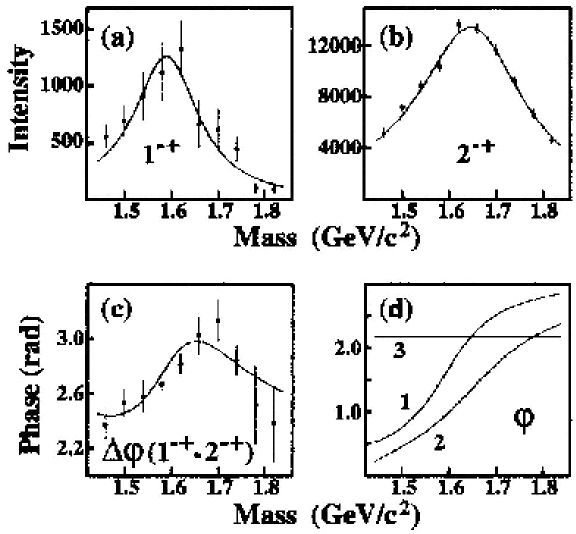

Figure 3: *The exotic* $\pi_1(1600)$ *observed by the VES and E852 Collaborations, here shown in E852* $\pi^- P \to (\rho\pi)^- P$ *data* [15].

magnetic fields, which gives a TM (1^-) gluon more energy than TE (1^+). The flux-tube model in contrast simply has a spatially excited interquark string and makes no reference to color field vectors. (Preliminary LGT results found the 1^{-+} hybrid at a significantly lower mass than the 0^{+-}, [10] as expected in the bag model but not the flux-tube model; more recent results by the same collaboration now find the 1^{-+} and 0^{+-} exotic hybrids rather closer in mass. [11]) The mass of the lightest hybrid meson multiplet is expected by theorists to be near 1.9 GeV. The bag model typically finds a somewhat lower scale of ca.1.5 GeV, which is now deprecated because it disagrees with LGT. This 1.9 GeV estimate was originally due to the flux tube model, [12, 13] and has been (approximately) confirmed by recent LGT studies, which find a mass of about 2.0 GeV for the lightest hybrid. [14] For a recent review of LGT predictions for these states see Michael. [3]

We now have strong evidence for a true $J^{PC} = 1^{-+}$ exotic at 1.6 GeV in $\rho\pi$ at BNL [15] and VES [16] (see Fig.3 for the $\rho\pi$ mode), and $\eta'\pi$ and $b_1\pi$ at VES. [16, 17] In addition a rather lighter state at 1.4 GeV in $\eta\pi$ has been reported by BNL and Crystal Barrel. [18, 19] Thus, experimental hadron spectroscopy may finally have found the hybrid mesons anticipated by theorists for about 25 years. Of course there is an unresolved concern that these experi-

mental masses are somewhat lighter than the theoretical expectation of $\approx$ 1.9-2.0 GeV. There are also nonexotic hybrid candidates such as the $\pi(1800)$; [20] a recent and reasonably complete review of light meson spectroscopy which discusses hybrid candidates in more detail was recently completed by Godfrey and Napolitano. [21].

Hybrid strong decays are in a confused state. The flux-tube model predicts that the dominant modes should be S+P two-body combinations such as πf_1 and πb_1. [12] The reported observations of hybrids however have for the most part been in the more familiar S+S modes such as $\pi\eta$, $\pi\eta'$ and $\pi\rho$, although there is some evidence for πb_1 [16] and πf_1. [22] VES has reported relative branching fractions for the $\pi_1(1600)$ exotic hybrid candidate that actually suggest comparable branching fractions to S+S and S+P modes. [16] Clearly the modelling of strong decays of hybrids is at an early stage, and the experimental determination of relative π_1 hybrid branching fractions will be a very useful contribution (assuming that these states persist with improved statistics!).

Since $q\bar{q}g$ hybrids span flavor nonets, there should be many more hybrids near 1.5 GeV if the reports of π_1 exotic hybrids near this mass are correct. Specific models of hybrids such as the flux-tube and bag models find that the majority of light hybrids have nonexotic J^{PC}. In the flux tube model the lightest hybrid multiplet contains five nonexotic quantum numbers,

$$J^{PC}(\mathrm{lightest\ flux-tube\ hybrid\ nonexotics}) = 0^{-+}, 1^{--}, 1^{++}, 1^{+-}, 2^{-+} \quad (3)$$

whereas in the bag model the lightest hybrid multiplet contains just three nonexotics,

$$J^{PC}(\mathrm{lightest\ bag-model\ hybrid\ nonexotics}) = 0^{-+}, 1^{--}, 2^{-+} \ . \quad (4)$$

Note that both models include a 1^{--} flavor nonet in the set of lowest-lying hybrid mesons. Thus the 1^{--} sector should show evidence of overpopulation relative to the naive quark model, which can be tested at DAFNE. We shall return to this topic in the next section.

2.3 Multiquarks and Molecules

In the 1970s it was thought that the existence of many basis states in the $q^2\bar{q}^2$ sector implied a very rich spectrum of multiquark resonances. Calculations

in specific models such as the MIT bag model and color-truncated potential models appeared to support this picture. However it was subsequently realized that the overlap of these multiquark basis states with the continuum of two color-singlet $(q\bar{q})(q\bar{q})$ mesons implied that the multiquark systems need not appear as resonances; they might instead simply be components of nonresonant two-meson continua.

An exception to this absence of four-quark resonances can occur if the multiquark system lies well below all two-body decay thresholds, or if there is a strongly suppressed coupling to the open decay channels; in these cases we might still expect to identify a bag-model "cluster" multiquark resonance.

Nature appears to favor a different type of multiquark system, in which largely unmodified color-singlet $q\bar{q}$ or qqq hadrons are weakly bound by the residual nuclear forces between color singlets. Examples of such quasinuclear multiquark systems abound; the table of nuclear species gives far more examples than we have of individual hadrons, and hypernuclei extend these systems into strangeness. In the mesonic sector, however, just two possible examples are widely cited, the scalar mesons $f_0(980)$ and $a_0(980)$.

These scalars are candidates for weakly bound $K\bar{K}$ nuclei, "molecules", [23] due to their masses and quantum numbers (which are those of an S-wave $K\bar{K}$ pair), and also because their hadronic couplings appear bizarre for $n\bar{n}$ states, which should be very broad and for $I = 0$ should couple strongly to $\pi\pi$. Another problem with a conventional assignment is the two-photon widths of these states, which are much smaller than expected for $q\bar{q}$ but are rather similar to predictions for $K\bar{K}$ bound states [24] or $ns\bar{n}\bar{s}$ four-quark clusters. [25] An interesting test of the nature of these states was proposed by Close, Isgur and Kumano; [26] the theoretical radiative branching fractions from the ϕ depend rather strongly on the quark model assignments, and for $q\bar{q}$ versus $K\bar{K}$ states are

$$B(\phi \to \gamma f_0(980), \gamma a_0(980)) = \left\{ \begin{array}{rcl} 4 \cdot 10^{-5} & : & K\bar{K} \text{ (both states)} \\ \simeq 1 \cdot 10^{-5} & : & f_0(980) = s\bar{s} \\ \leq 10^{-6} & : & f_0(980), a_0(980) = n\bar{n} \ . \end{array} \right. \tag{5}$$

Close *et al.* note that the ratio $\phi \to \gamma a_0(980)/\gamma f_0(980)$ is also of interest, since it can distinguish between different multiquark spatial wavefunctions. For a $K\bar{K}$ molecule this ratio is 1, whereas for an $(ns)(\bar{n}\bar{s})$ system it is 9. [26]

Table 2: *Suggested excited $n\bar{n}$ multiplets.*

nL	M(GeV)	representative WHS99 candidates
2S	1.4	$\rho(1450), \pi(1300)$
3S	1.8	$\pi(1740)$
4S	2.1	$\rho(2150)$
2P	1.7	$f_2(1650), a_2(1700), a_1(1700)$
3P	2.08	$f_0(2095), a_1(2100), a_0(2050)$
4P	2.34	$f_0(2335), a_1(2340)$
2D	2.0	$\omega_3(1950), \eta_2(2040)$
3D	2.3	$\rho_3(2300), \omega_3(2215), \eta_2(2300)$
2F	2.29	$f_4(2290), f_3(2280), a_4(2280), a_3(2310)$

At this meeting we have heard that the new experimental results from VEPP [27] are not far from the Close *et al.* predictions for a $K\bar{K}$ molecule. (The VEPP experimental branching fractions $B(\phi \to \gamma f_0(980), \gamma a_0(980))$ are somewhat larger than $4 \cdot 10^{-5}$, but are roughly consistent with Close *et al.* given the current errors.) Earlier experimental indications of much larger branching fractions to the 980 MeV states were biased by large nonresonant contributions well below 980 MeV, which had not clearly been identified.

Presumably there are many meson-meson bound states, since many other meson pairs experience attractive residual nuclear interactions. Unlike glueballs and hybrids, the spectrum of molecular states beyond $K\bar{K}$ and the nuclei and hypernuclei has received little theoretical attention. There are quark model and meson-exchange model predictions that some vector meson pairs may bind, [28, 29] but to date there has been little systematic investigation of the expected spectrum. As our understanding of residual hadronic forces improves, we can expect this to be one of the interesting areas of development in hadron spectroscopy in the coming years.

2.4 Conventional $q\bar{q}$ Mesons

As a background to these various hadronic exotica we have a spectrum of conventional $q\bar{q}$ states, which must be identified if we are to isolate non-$q\bar{q}$ states. Since many of the light non-$q\bar{q}$ states predicted by theorists have masses and quantum numbers that allow confusion with excited $q\bar{q}$ states, it is important to establish the light $q\bar{q}$ spectrum below 2.5 GeV as completely as possible.

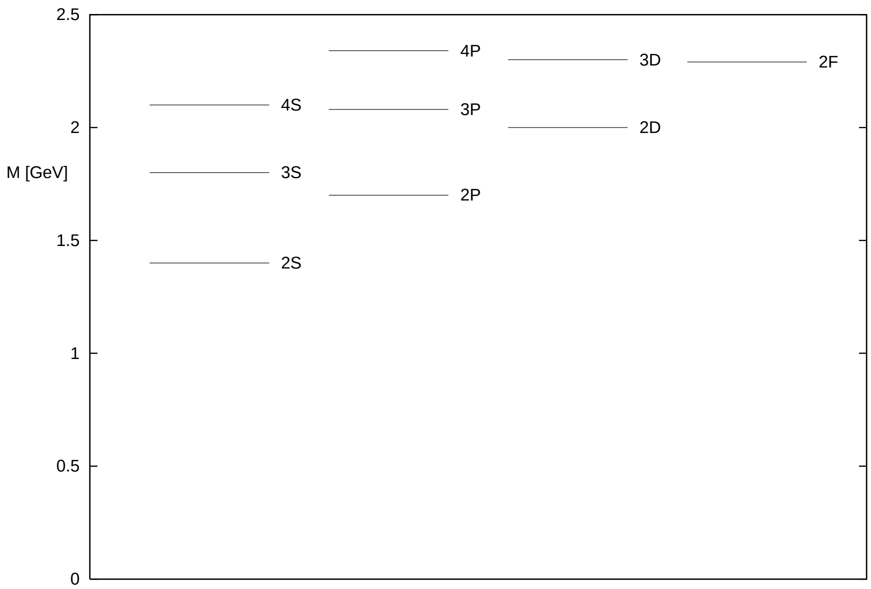

Figure 4: *Excited $n\bar{n}$ multiplets suggested by recent data (see Table 1).*

Identification of the $q\bar{q}$ and non-$q\bar{q}$ states in the spectrum will require that we clarify meson spectroscopy to a mass of at least 2.5 GeV, so that the pattern of glueballs, hybrids and multiquarks can be established through the identification of sufficient examples of each type of state.

There has been impressive experimental progress in the identification of the (presumably $q\bar{q}$) light meson spectrum in recent years. In Fig.4 we show the masses of the relevant radially- and orbitally-excited multiplets for which candidate states were reported at the WHS99 hadron spectroscopy meeting in Frascati earlier this year, from a review by Barnes. [30] It appears that almost all the $q\bar{q}$ multiplets expected below 2.5 GeV have now been identified. [31] These multiplet masses and some representative candidates reported at the WHS99 meeting are given in Table 1.

Surprisingly, these orbital+radial multiplets lie at rather lower masses than predicted by Godfrey and Isgur; [32] compare the predicted and observed

2P and 2D multiplet masses:

$$M(2P)|_{\rm GI} \approx 1.80 \text{ GeV}, \tag{6}$$

$$M(2P)|_{\rm expt.} \approx 1.7 \text{ GeV}. \tag{7}$$

$$M(2D)|_{\rm GI} \approx 2.14 \text{ GeV}, \tag{8}$$

$$M(2D)|_{\rm expt.} \approx 2.0 \text{ GeV}. \tag{9}$$

Evidently, experiment is finding the 2P and 2D multiplets about 0.1-0.2 GeV lower in mass than predicted by the Godfrey-Isgur model. If this discrepancy is confirmed it will be important to determine whether this requires some important modification of the model.

Thus far it has been possible to identify these $q\bar{q}$ multiplets largely by the systematics of masses. This is possible because multiplet splittings decrease rapidly with increasing L, so we are fortunate to find the members of a given higher-L multiplet at very similar masses. In principle one might also distinguish between $q\bar{q}$ states and non-$q\bar{q}$ exotica such as glueballs and hybrids through their strong decay branching fractions and amplitudes. Detailed predictions are now available for these branching fractions for all $n\bar{n}$ states expected up to 2.1 GeV, [33] and for a few specific cases at higher mass. [34] If our decay models are accurate, these higher quarkonia often have very characteristic branching fractions, which should be quite distinct from glueball or hybrid decays. Unfortunately, the ^{3}P$_0$ decay model and the closely related flux-tube decay model have not been tested carefully, except in a few cases such as $b_1 \to \omega\pi$ and $a_1 \to \rho\pi$. (These transitions have both S and D amplitudes, and their D/S ratios are sensitive tests of the decay models and are in good agreement with experiment.) A new and very important test of the decay models was recently reported by VES. [17] In both the ^{3}P$_0$ and flux-tube decay models, transitions of the type $(S_{q\bar{q}} = 0) \to (S_{q\bar{q}} = 0) + (S_{q\bar{q}} = 0)$ are forbidden, due to the spin-1 character of the decay model pair creation operator. This implies for example that $\pi_2(1670) \to b_1\pi$ should vanish, although it is nominally an allowed D-wave strong decay. VES finds a rather tight upper limit on this transition,

$$B(\pi_2(1670) \to b_1\pi) < 0.19\% \ (2\sigma \ c.l.) \ . \tag{10}$$

This null result is very reassuring, but does not uniquely confirm a ^{3}P$_0$-type decay model; the same theoretical zero follows for example from OGE pair production. [35] A second test due to VES which also involves the $\pi_2(1670)$ does *not* agree with the expectations of the decay models: $B(\pi_2(1670) \to \omega\rho)$ should be about 16%, [33] and the spin-1 decay operator implies that the $\omega\rho$ final state should have spin-1, with the ^{3}P$_2$ $\omega\rho$ amplitude dominant. VES instead finds

$$B(\pi_2(1670) \to \omega\rho \ (S=2)) = 1.9(0.4)(1.0)\% \tag{11}$$

and

$$B(\pi_2(1670) \to \omega\rho \ (S=1)) = 0.9(0.2)(0.3)\% \ , \tag{12}$$

which suggests that strong decays in this sector may not agree with the decay models.

Until such time as we can test the predictions of the decay models against a wide range of accurately determined experimental decay amplitudes and branching fractions, it will remain unclear whether the predictions are indeed reliable, or accidentally happen to work well for a few special cases. For this reason it would be extremely useful to determine the relative branching fractions of all two-body modes of higher-mass states such as the excited vectors $\rho(1465)$ and $\rho(1700)$. The current situation, with most modes unmeasured or reported only as "seen" (Tables 2-4) does not allow one to make progress in the very important subject of strong decays. An accurate determination of excited vector decay amplitudes would be an extremely useful DAFNE contribution, as we shall now discuss.

3 Exotica and excited vector mesons at DAFNE

The "vector sector" affords a very interesting subject for future investigation at DAFNE. This topic was studied at Frascati in the past at ADONE, [36] *albeit* with much lower luminosity. e^+e^- annihilation is of course the ideal technique for making these states, since single photons make 1^{--} uniquely. At the time this appeared to be a rather straightforward problem in hadron spectroscopy, since the quark model predictions of excited $J^{PC} = 1^{--}$ vector mesons with radial and orbital excitations (with both 2^3S$_1$ and ^{3}D$_1$ expected at about $1\frac{1}{2}$ GeV) were uncontroversial. Unfortunately it was found that the

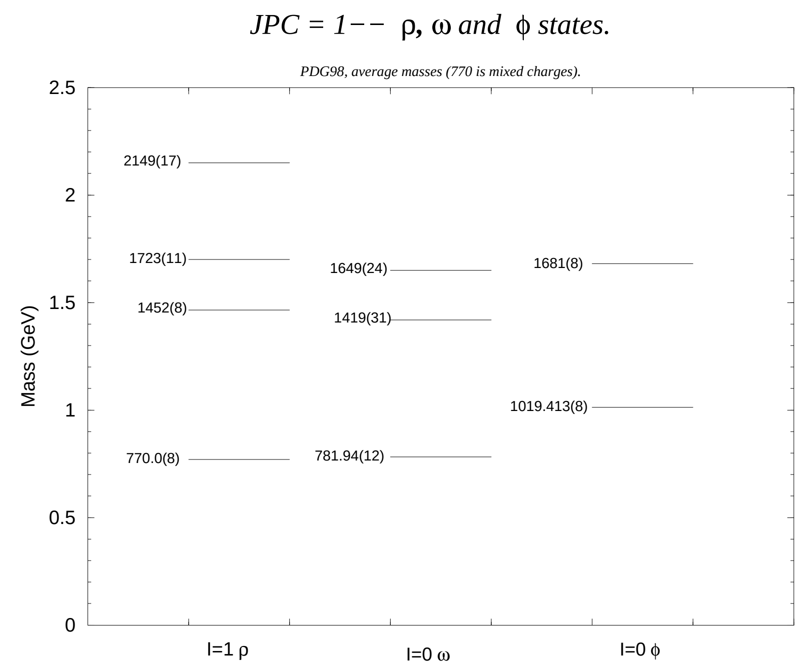

Figure 5: *Excited vector meson spectroscopy according to the 1998 PDG.*

excited vectors were rather broad, overlapping states, so the radial and orbital excitations could not be clearly separated. This subject has been reviewed by Donnachie, [37, 38] who discusses it in more detail in these proceedings.

The subject advanced somewhat with studies of the ρ-sector in both 2π and 4π modes, which lead the PDG in 1988 to distinguish two states, the $\rho(1450)$ and the $\rho(1700)$. (The current status of light vector spectroscopy according to the PDG is shown in Fig.5.) These are usually indentified with the 2S (radial) and D (orbital) excitations respectively, since the masses correspond approximately to quark potential model expectations. (There are problems with this simple assignment, such as the surprisingly large e^+e^- coupling of the nominally $L = 2$ $\rho(1700)$, which has a vanishing wavefunction at contact.)

There are analogous states reported in the isosinglet sector, the $\omega(1420)$ and $\omega(1600)$. (The situation may be more complicated. See in particular the recent results on $e^+e^- \to \pi^+\pi^-\pi^o$ from VEPP, [40] which show a very low

Table 3: *Theoretical* [33, 39] *and experimental* [4] *two-body partial widths and total widths (MeV) and branching fractions of excited* ρ *states. Theoretical predictions are for a* $\rho_{2S}(1465), \rho_D(1700)$ *and a* $\rho_H(M_H)$*, with* $M_H = 1.5$ *GeV and* 2.0 *GeV. For the* $\rho_H(2000)$*,* $a_2\pi$ *and* K_1K *modes (not shown) are also important.*

Γ_i:	$\pi\pi$	$\omega\pi$	$\rho\eta$	$\rho\rho$	KK	K^*K	$h_1\pi$	$a_1\pi$	Γ_{tot}
ρ_{2S}	74	122	25	-	35	19	1	3	279
ρ_D	48	35	16	14	36	26	124	134	435
$\rho_H(1500)$	0	5	1	0	0	0	0	140	≈ 150
$\rho_H(2000)$	0	8	7	0	0	4	0	170	≈ 340
$B_{expt.}$:									
$\rho(1465)$	seen	$< 2\%$	$< 4\%$	-	$< 0.16\%$	-	-	-	310(60)
$\rho(1700)$	seen	seen	seen	-	seen	seen	$\rho\pi\pi$ *dom.*	$\rho\pi\pi$ *dom.*	240(60)

Table 4: *As Table 2 but for excited* ω *states. Theoretical predictions are for an* $\omega_{2S}(1419), \omega_D(1649)$ *and an* $\omega_H(M_H)$*, with* $M_H = 1.5$ *GeV and* 2.0 *GeV.*

Γ_i:	$\rho\pi$	$\omega\eta$	$\omega\eta'$	$b_1\pi$	KK	K^*K	$K_1^{<}K$	$K_1^{>}K$	Γ_{tot}
ω_{2S}	328	12	-	1	31	5	-	-	378
ω_D	101	13	-	371	35	21	-	-	542
$\omega_H(1500)$	20	1	-	0	0	-	-	-	≈ 20
$\omega_H(2000)$	40	20	30	0	0	30	40	60	≈ 220
$B_{expt.}$:									
$\omega(1419)$	dom.								174(59)
$\omega(1649)$	seen			$\omega\pi\pi$ *seen*					220(35)

Table 5: *As Table 2 but for excited* ϕ *states. Theoretical predictions are for a* $\phi_{2S}(1680), \phi_D(1850)$ *and a* $\phi_H(2150)$*.*

Γ_i:	KK	K^*K	K^*K^*	$K_1^{<}K$	$K_1^{>}K$	K_2K	$\phi\eta$	$\phi\eta'$	Γ_{tot}
ϕ_{2S}	89	245	-	-	-	-	44	-	378
ϕ_D	65	75	5	465	-	-	29	-	638
$\phi_H(2150)$	0	15	0	60	125	20	8	2	≈ 230
$B_{expt.}$:									
$\phi(1680)$	seen	dom.							150(50)

mass peak at about 1220 MeV.) In the ϕ sector we have evidence for only a single excitation, the $\phi(1680)$.

Interest in the excited vectors has increased with the realization that the lightest hybrid meson multiplet includes a 1^{--} (in both the flux-tube and bag models), and that these hybrid vectors are predicted to be rather narrow. Indeed, in the hybrid meson decay calculations of Close and Page (using the Isgur-Kokoski-Paton flux-tube model) the narrowest hybrid found was the ω-flavor 1^{--}. (See Table 3 for the predicted partial widths of this vector hybrid.) The Close-Page calculations assumed a mass of 2.0 GeV for the ρ_H and ω_H hybrid vectors, but given the reports of the $\pi_1(1400)$ and $\pi_1(1600)$ hybrid candidates, one should also consider the possibility that the lowest hybrid multiplet lies at about 1.5 GeV. This would give us a third 1^{--} level roughly degenerate with the quark model 2S and D levels, and such light vector hybrids could be very narrow (see Table 3); a hypothetical $\omega_H(1500)$ is predicted to have a total width of only about 20 MeV! If the 1^{--} hybrid states are not found at this low mass, one might question the reports of π_1 1^{-+} exotics near 1.5 GeV.

The topic of vector meson spectroscopy in this mass region was recently reviewed by Donnachie and Kalashnikova, [38] who concluded that additional vectors beyond the expected $q\bar{q}$ states are indeed required to fit the data in both $I = 0$ and $I = 1$ channels. In $I = 1$ in particular, the weakness of $e^+e^- \to \pi^+\pi^-\pi^o\pi^o$ relative to $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cannot be explained by the expected $\rho(1700)$ decays alone.

In principle one should be able to separate the 2S, D and H (hybrid) states by studies of their relative decay branching fractions. In Tables 2-4 we show theoretical predictions for the different types of states, compared to 1998 PDG results for experimental branching fractions. The relative strength of the broad 4π modes $h_1\pi$ and $a_1\pi$ is quite sensitive to the type of parent resonance, and could serve as a useful discriminator if the decay models are accurate. The theoretical expectation is that the D state should populate both modes, H should only populate $a_1\pi$, and the 2S state does not couple significantly to either of these modes. How well do these theoretical predictions agree with experiment?

The experimental branching fractions of excited vectors, as reported in the 1998 PDG, are also shown in Tables 2-4. It is clear at a glance that experiment is in a woeful state. Almost nothing is known about the decays of excited ω and

ϕ states. (Note that excited ϕ vectors can be isolated by studying the $s\bar{s}$-filter mode $\phi\eta$, which was apparently not attempted previously.) In the ρ sector, there are promising indications that the $\rho(1700)$ may be observed in many of the expected channels, but there is almost no quantitative information about relative branching fractions which we require for tests of the decay models. In contrast, there are strong limits claimed for $\rho(1465)$ branching fractions, which appear to be very different from expectations for a simple 2S radial excitation. Note especially the tight limit $B(\rho(1465) \to \omega\pi) < 2\%$. Taken literally, this result is very interesting in that it argues strongly against a 2S assignment for the $\rho(1465)$. (Compare the ρ_{2S} and $\rho(1465)$ entries in Table 2.) Unfortunately it is difficult to reconcile this number with the reported *dominance* of $\omega(1419) \to \rho\pi$ (Table 3), since that decay differs from $\rho(1465) \to \omega\pi$ only by a flavor factor of 3 (favoring $\omega(1419) \to \rho\pi$) and minor changes in phase space.

Recently the Crystal Barrel Collaboration attempted to separate the contributions of the $\rho(1465)$ and $\rho(1700)$ to the various 4π final states. Initially the results appeared consistent with the usual quark model assignments 2S and D, [41] but the most recent work [42] has found that essentially all broad 4π modes ($a_1\pi, h_1\pi, \pi(1300)\pi, \rho\rho$ and $\rho\sigma$) are important in the decays of both the $\rho(1465)$ and the $\rho(1700)$! Unfortunately the statistical errors of this many-parameter fit are rather large, so each mode typically has a fitted branching fraction about 2σ from zero. The excited vectors would evidently benefit from a study at an e^+e^- facility such as DAFNE, where the complication of competing amplitudes in many other J^{PC} channels is not present.

In view of the poorly constrained and perhaps inconsistent branching fractions evident in the PDG, the most reasonable approach in future would probably be to study as many of the quasi-two-body decay modes in Tables 2-4 as possible, determine numerical values for the relative branching fractions, and carry out a global fit of each flavor sector with an assumed two versus three parent resonances in each flavor.

4 Two-photon couplings

In the opinion of at least two LEAR experimentalists, [43] using $\gamma\gamma$ collisions to clarify the scalar sector is the most interesting contribution DAFNE could make to spectroscopy.

Two-photon couplings of resonances can be inferred by measurement of

the cross section

$$\sigma(e^+e^- \to e^+e^- R) \tag{13}$$

which is proportional to the two-photon width $\Gamma\gamma\gamma$ of the resonance R, as discussed in Sec.36.3 of the 1998 PDG. [4] Two-photon widths of $C = (+)$ resonances have been measured at several e^+e^- facilities in the past, most recently at LEP. [44, 45] These are especially interesting quantities because they show considerable variation between $q\bar{q}$ and non-$q\bar{q}$ states, and if determined with sufficient accuracy they could be used for example to solve the problem of the assignments of the various light scalars. This subject attracted considerable interest and effort previously, but as $e^+e^- \to e^+e^- R$ is an $O(\alpha^4)$ process and the cross section falls rapidly with M_R, it was not possible to obtain adequate statistics for a definitive analysis.

The two-photon partial widths of $q\bar{q}$ states within a flavor multiplet in the SU(3) limit are in the ratio

$$\Gamma\gamma\gamma \quad f \ : \ a \ : \ f' \ = \ 25 \ : \ 9 \ : \ 2 \ \ , \tag{14}$$

so if a candidate $q\bar{q}$ state such as the 2^{++} $f_2(1270)$ is reported, one should also observe its flavor partners at about this relative strength. For example, the $\Gamma\gamma\gamma$ widths of the 2^{++} multiplet are

$$\Gamma\gamma\gamma(2^{++}) \ \ f_2(1270) : a_2(1310) : f'(1525) \ = \ 2.8(4)\text{keV} : \ 1.00(6)\text{keV} : \approx 0.1\text{keV} \ . \tag{15}$$

(Moderate suppression of the $s\bar{s}$ coupling is expected theoretically due to the heavier strange quark mass.)

Scalars are predicted to have very characteristic two-photon couplings. The largest $\Gamma\gamma\gamma$ width expected for any $q\bar{q}$ meson is for the $^3\mathrm{P}_0$ f_0 scalar; in the nonrelativistic quark model it has a $\Gamma\gamma\gamma$ width 15/4 times that of the f_2, and with relativistic corrections [46] the ratio is reduced to ≈ 2. Thus for a scalar $n\bar{n}$ partner of the $f_2(1270)$ we expect a two-photon width of about 5 keV. An $f_0(1250)$ scalar signal of about this strength was observed by the Crystal Ball Collaboration in $\gamma\gamma \to \pi^o\pi^o$ at DESY, [47] and may be the long-sought and still obscure $n\bar{n}$ scalar. In contrast, a pure scalar glueball should have a much smaller two-photon width, since it has no direct coupling to photons. The recent ALEPH results on $\gamma\gamma$ couplings of resonances appear to support the $f_0(1500)$ as a glueball candidate, since their upper limit [44]

$$\Gamma\gamma\gamma(f_0(1500)) \ < \ 0.17 \text{ keV } (95\% \ c.l.) \tag{16}$$

is far below the ca. 5 keV expected for an $n\bar{n}$ scalar.

The various $n\bar{n} \leftrightarrow G \leftrightarrow s\bar{s}$ mixing models in contrast would predict $\Gamma\gamma\gamma$ widths roughly proportional to each state's $n\bar{n}$ amplitude squared, and so could be tested by the relative strength of each scalar resonance in $\gamma\gamma \to \pi^o\pi^o$. Finally, $K\bar{K}$ molecules [24] and multiquark states [25] are predicted to have much smaller $\Gamma\gamma\gamma$ widths than the corresponding $n\bar{n}$ states, which is in agreement with the sub-keV $\Gamma\gamma\gamma$ values reported for the $f_0(980)$ and $a_0(980)$.

In contrast with the non-observation of the scalar glueball candidate $f_0(1500)$ in $\gamma\gamma$, we now have clear evidence for the pseudoscalar $\eta(1440)$ in $\gamma\gamma \to K_s K^{\pm}\pi^{\mp}$, reported by the L3 Collaboration. [45] Once a glueball candidate (this assignment is now implausible due to the high mass predicted for the pseudoscalar glueball by LGT), this state appears most likely to be a radially-excited $q\bar{q}$. Similarly there is a possible observation of the scalar glueball candidate $f_0(1710)$ by L3 in $\gamma\gamma \to K_s K_s$, although this is preliminary. If the $f_0(1710)$ appears clearly in $\gamma\gamma$ at the rate expected for a radially-excited $2^3\mathrm{P}_0$ $n\bar{n}$ state, we may be able to eliminate it as a glueball candidate in favor of the $f_0(1500)$. Clearly, accurate measurements of scalar $\Gamma\gamma\gamma$ couplings show great promise as a technique for solving the long standing problem of the nature of the various f_0 scalar resonances.

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